Coherent structure and turbulent mixing in the hurricane boundary layer observed by unmanned aircraft

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With many thanks to the COYOTE team!

Thursday (12 July)

10:20-12:30: Plenary Session 8: Severe Weather and Community Discussion (Kittredge)

10:20-10:40 J. Cione: Coyote UAS observations in Hurricane Maria (2017)

What is Coyote UAS?

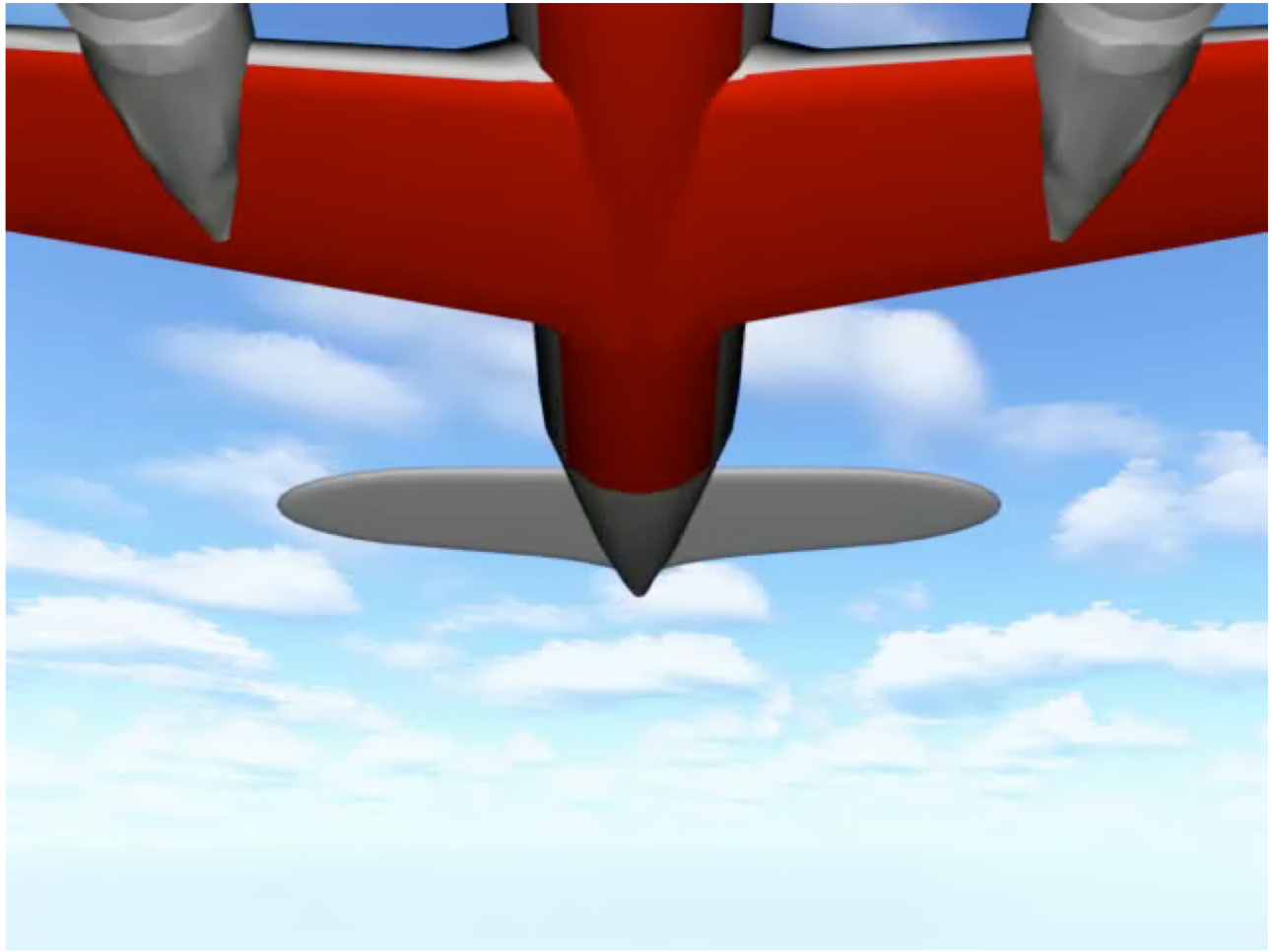
An experimental, small, semi-autonomous, "uncrewed" aircraft, deployed from a "crewed" aircraft

P3 Orion (NOAA AOC); Crewed Aircraft

Joe Cione (NOAA/AOML/HRD, NOAA/ESRL/PSD)

Coyote UAS (Raytheon Corp.); Uncrewed Aircraft System

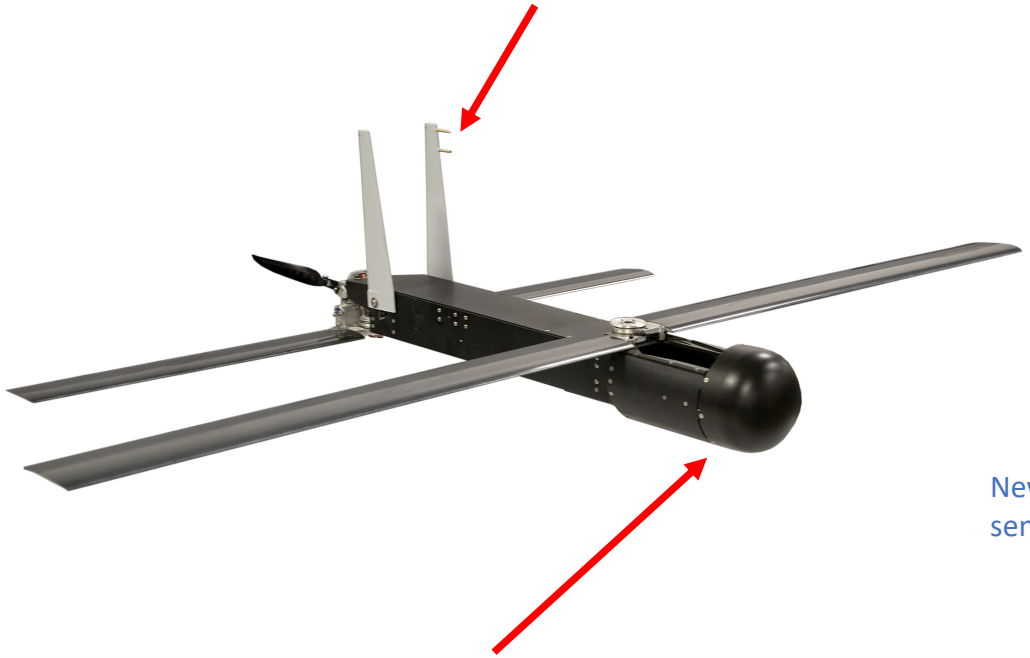
Deployment of Coyote UAS



Atmospheric Measurements

For more details, see Cione et al. 2016 (*Earth and Space Science*)

Wind determined using onboard devices (eg, pitostatic pressure): up to 10 Hz



New for 2017: infrared (IR) sensor for sea-surface temperature

Table 2. Specifications for the Meteorological Sensors Aboard the Coyote

Sensor	ManufacturerModel	Range	Tolerance	Response Time (s)	Sampling Rate (Hz)
Pressure	HoneywellSCCP15ASMTP	5–1070 mb	±0.5 mb	<1.0	3
Temperature	SHIBAURAPB5	−80–60°C	±0.3°C	<2.0	2
Humidity	E + EHC103M2	0–100%	±5%	<5.0 at 25°C	1

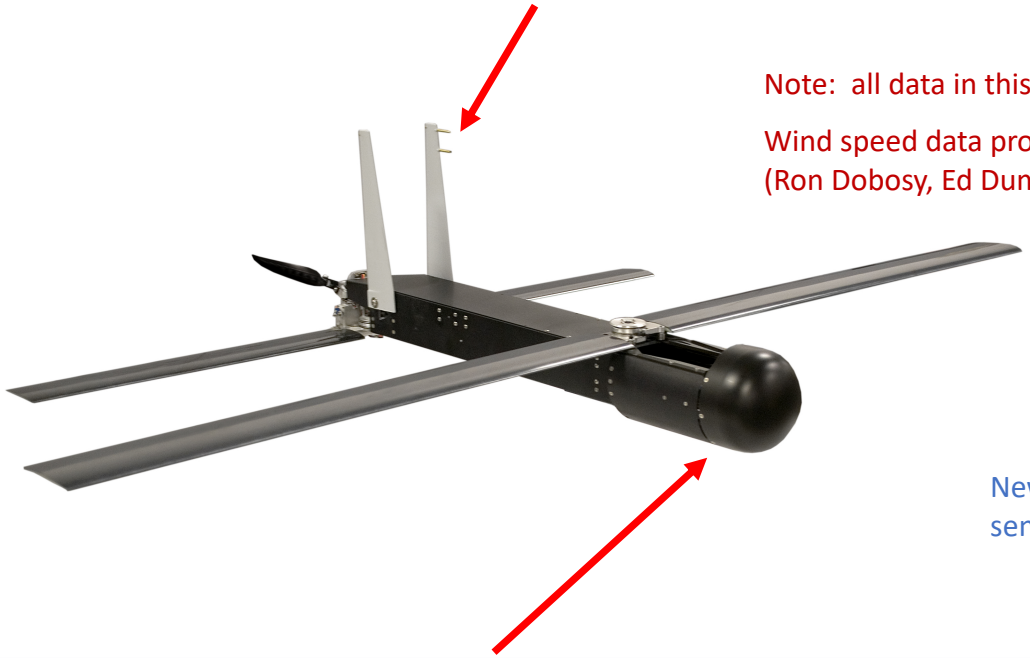
Atmospheric Measurements

For more details, see Cione et al. 2016 (*Earth and Space Science*)

Wind determined using onboard devices (eg, pitostatic pressure): up to 10 Hz

Note: all data in this talk are preliminary

Wind speed data provided by NOAA/ARL/ATDD
(Ron Dobosy, Ed Dumas, Michael Buban, Temple Lee)



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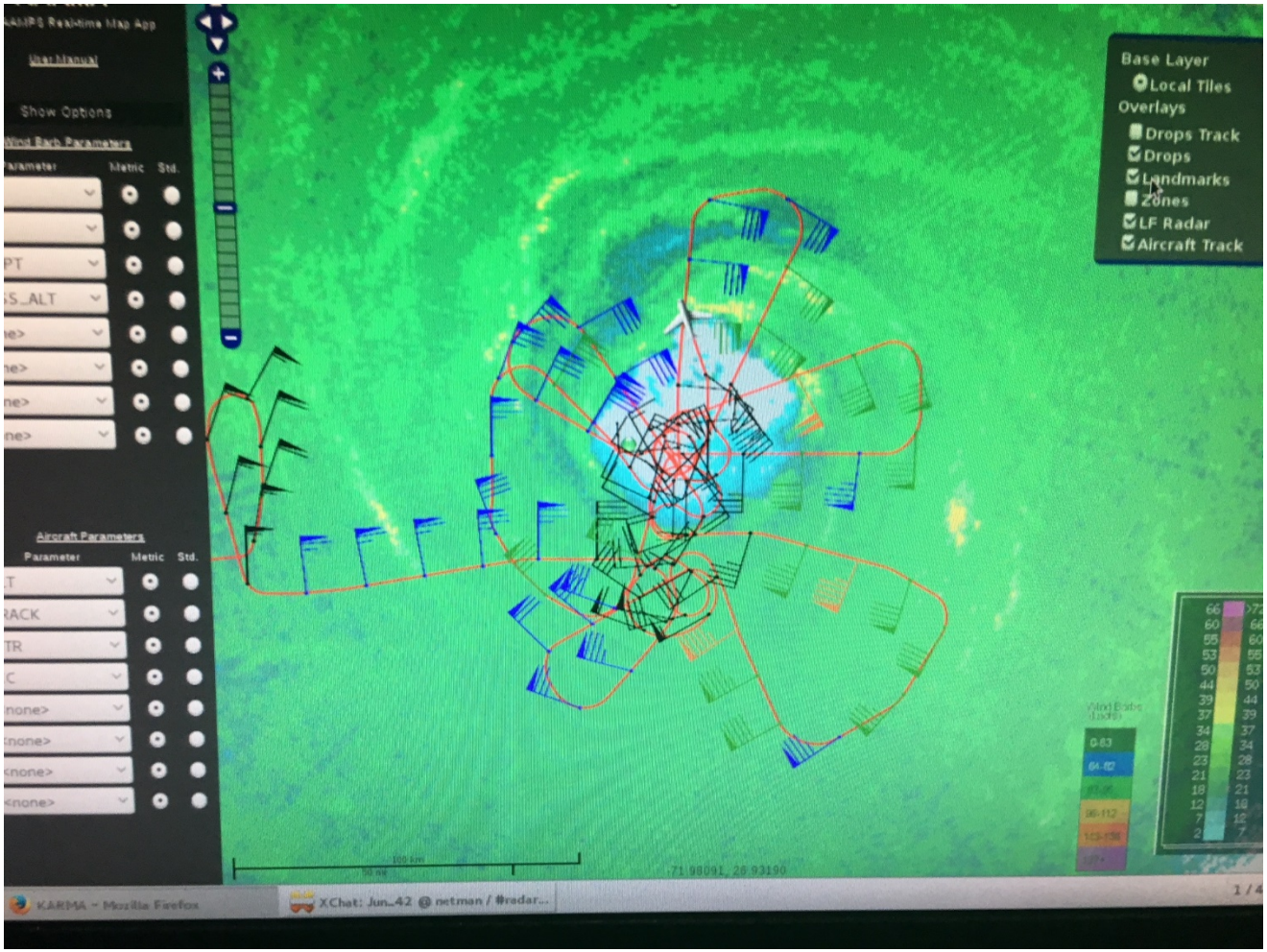
P3 flight pattern

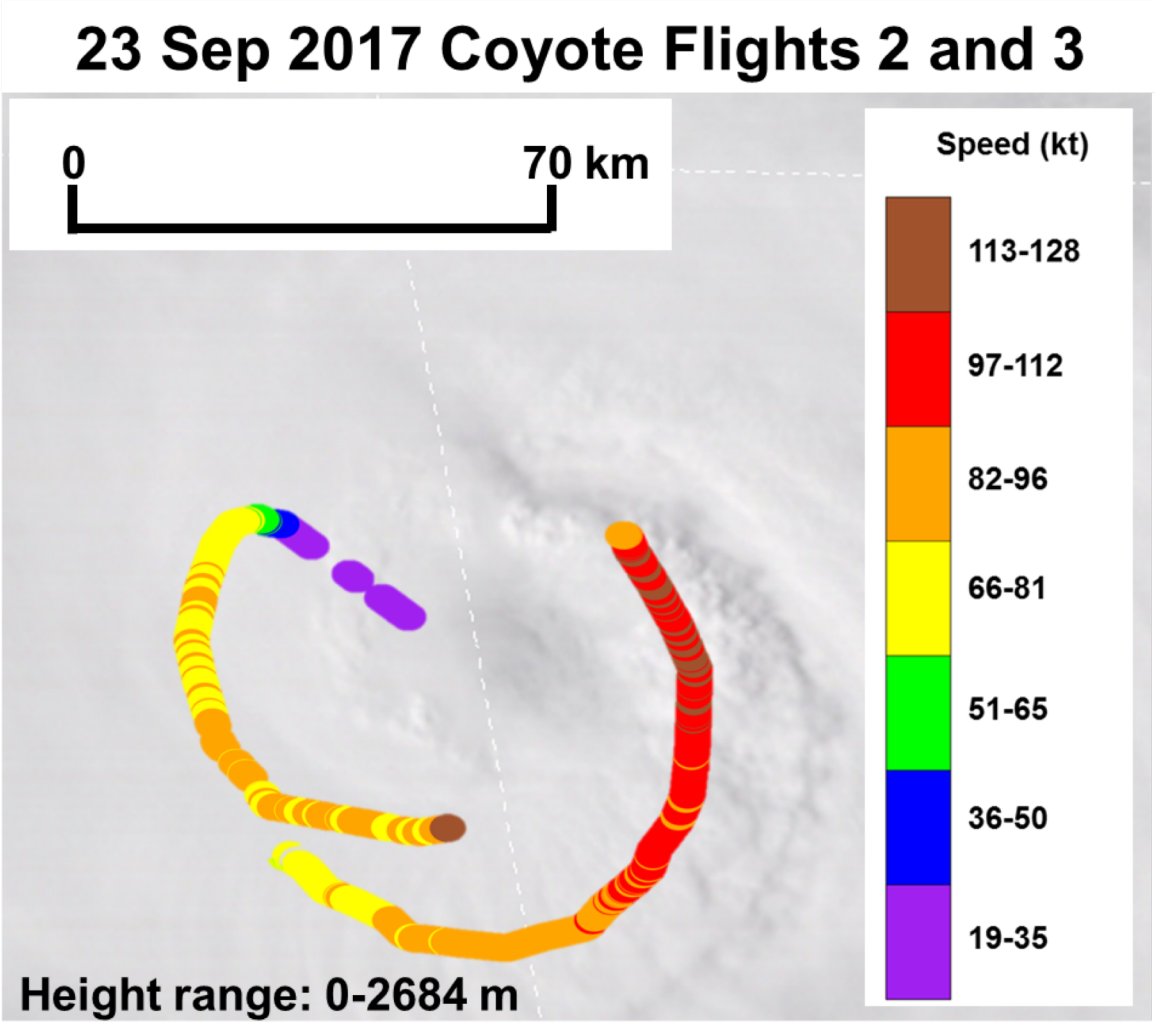
Flight track - orange line

Background color – radar reflectivity



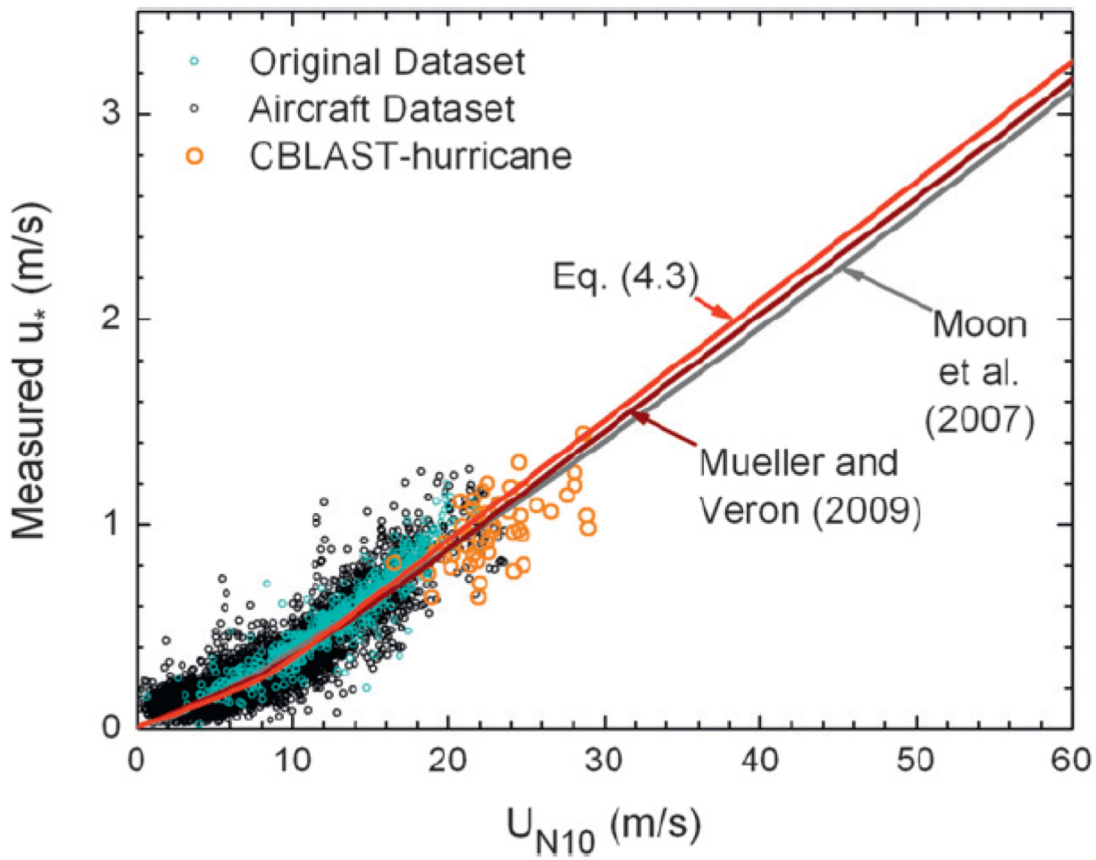
P3 follows the SUAS after releasing it. A total of 9 eyewall penetrations were completed for each P3 flights. P3 was circling in the eyewall when the SUAS was operated.

SUAS (Coyote) flight track and wind speed



Friction velocity (u_*)

$$|\tau| = \left[\overline{u'w'}^2 + \overline{v'w'}^2\right]^{1/2} = u_*^2$$



Andreas et al. (2012, JAS)

Two New Capabilities …

2. Large-Eddy Simulation (LES): High-resolution model simulations

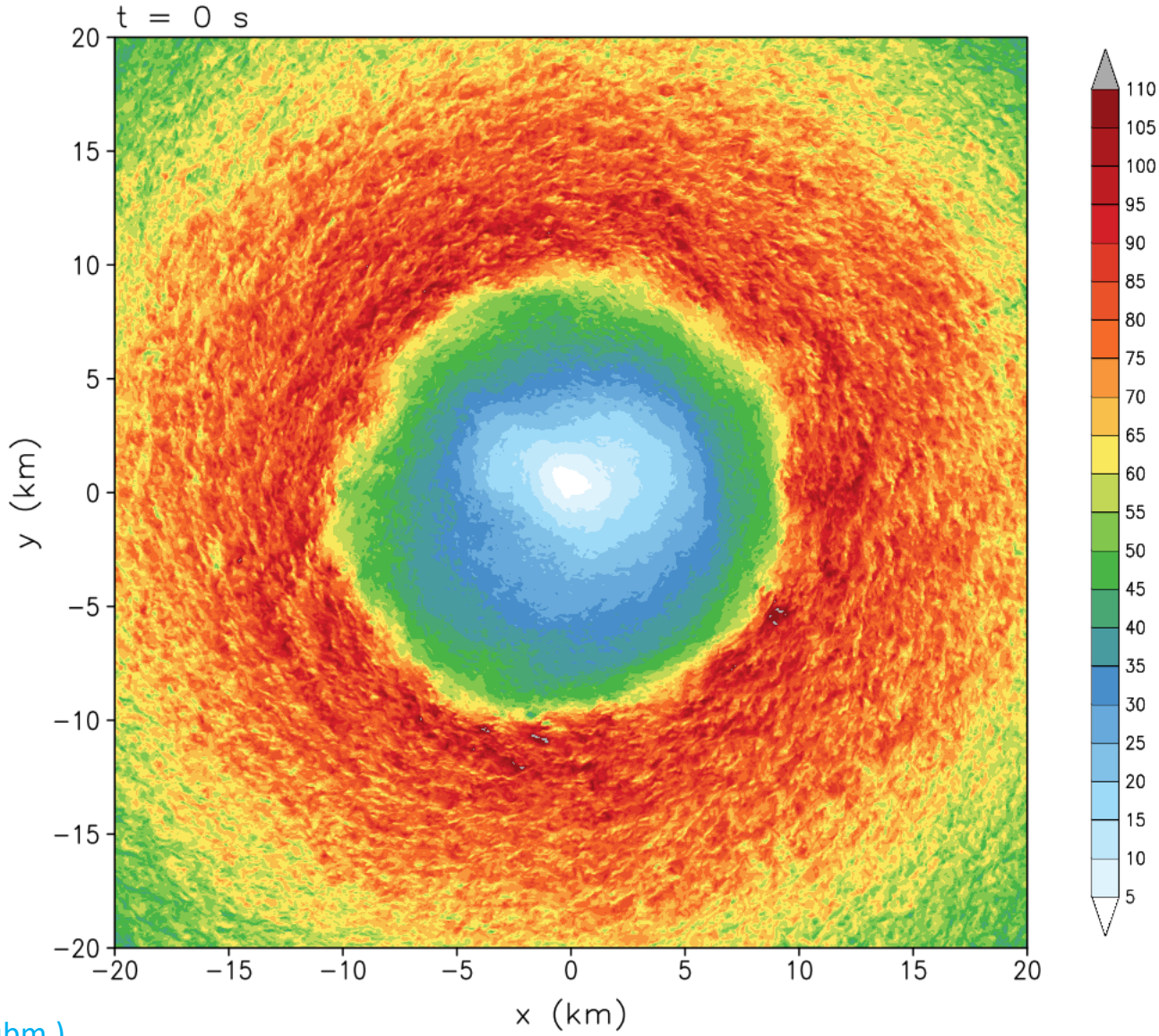
Details:

Wind speed (m s^{-1})
at z = 100m

$\Delta x = \Delta y = 31$ m
$\Delta z = 15.5$ m

over 80 km x 80 km inner fine mesh (entire domain is 3000 km x 3000 km)

5-min animation, image every 2 s

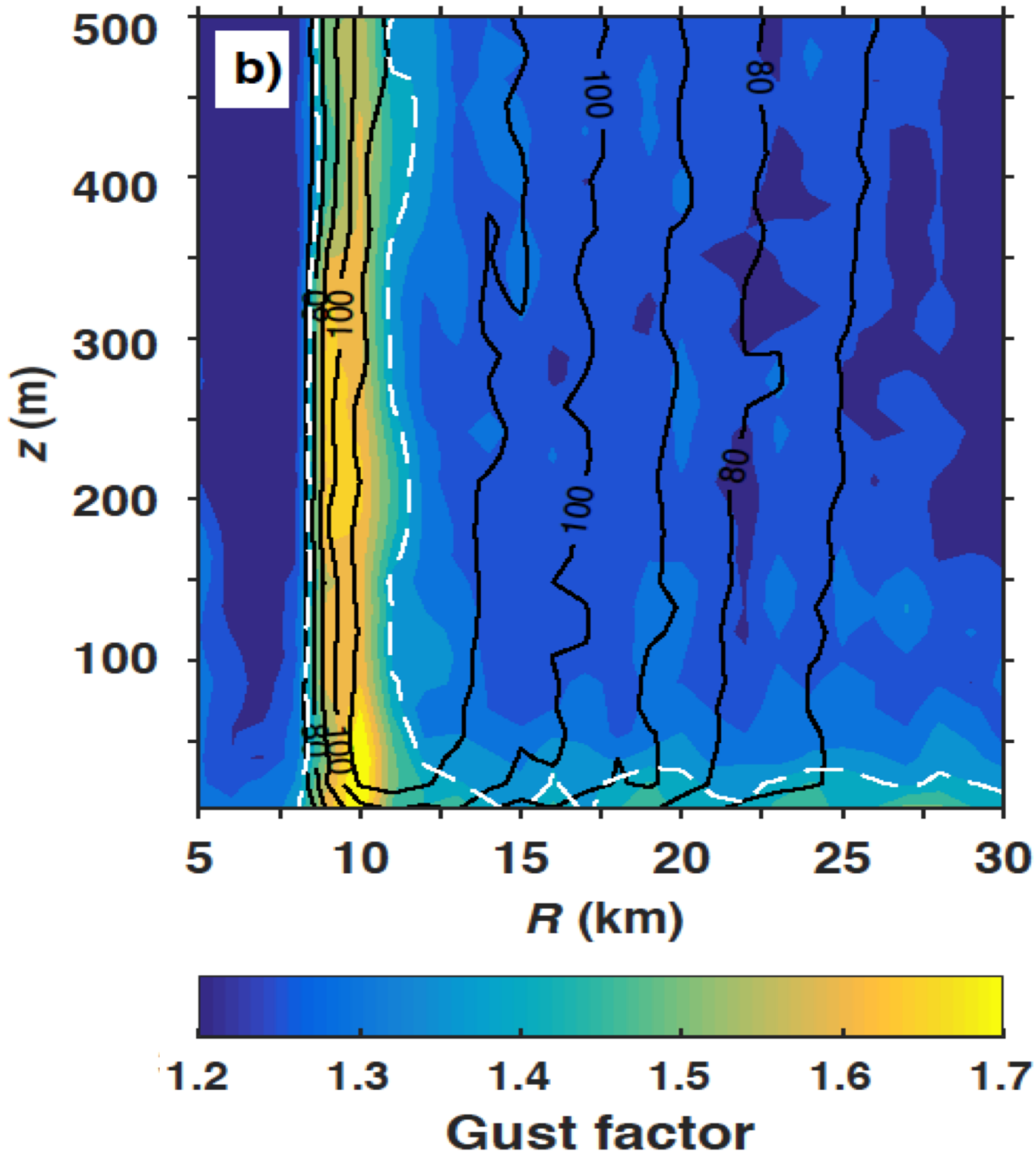


Richter et al. (2016, JAS)
Worsnop et al. (2017, GRL)
Stern and Bryan (2018, MWR,subm.)

Gust Factor

Color shading:
Maximum Gust Factor, defined as
GF = (max 3-s avg.)
/ (10-min avg.)

Black contours:
max. 3-s-avg wind gust



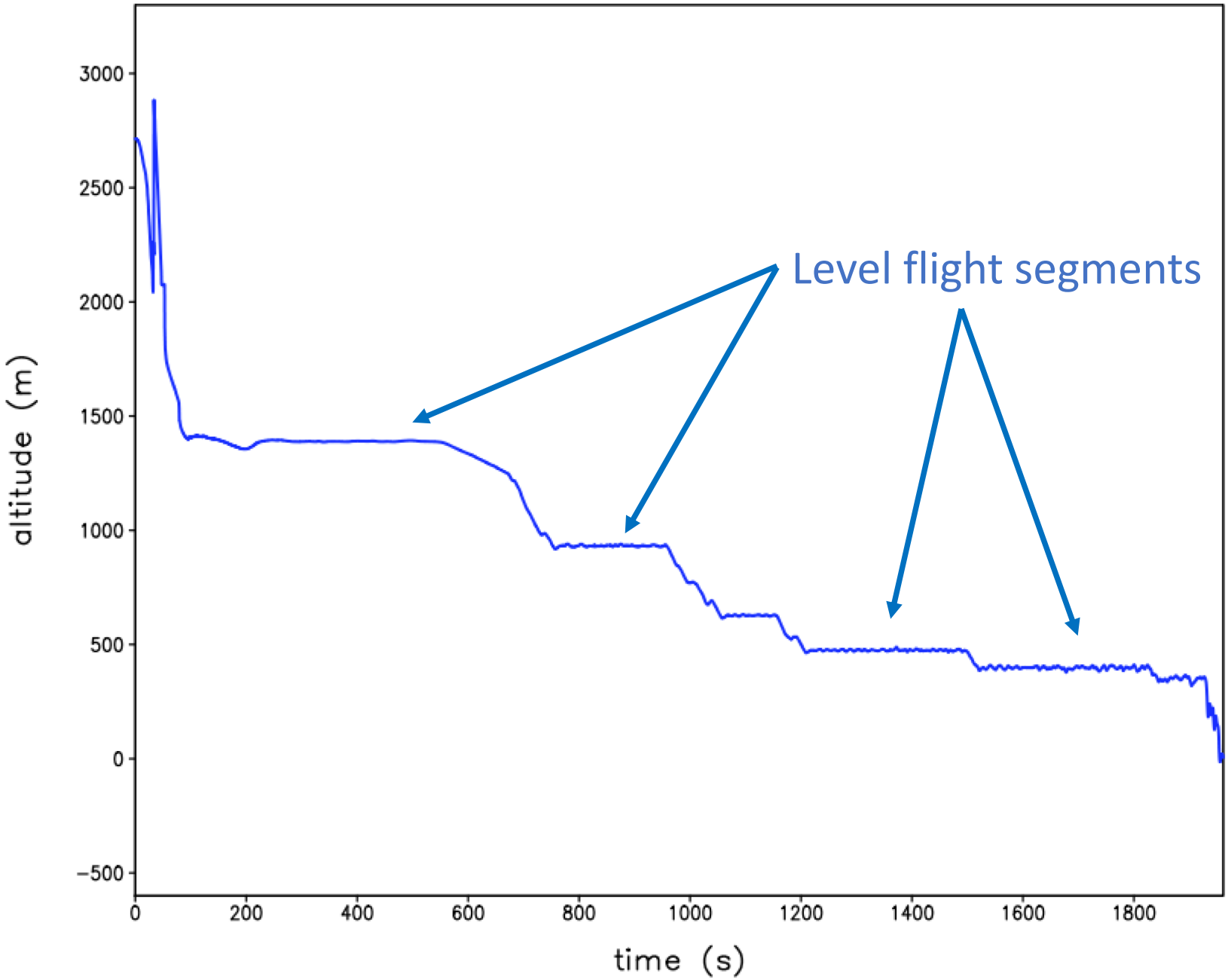
Worsnop et al. (2017, GRL)

Using Coyote UAS Observations to Evaluate Large-Eddy Simulations (and Vice Versa)

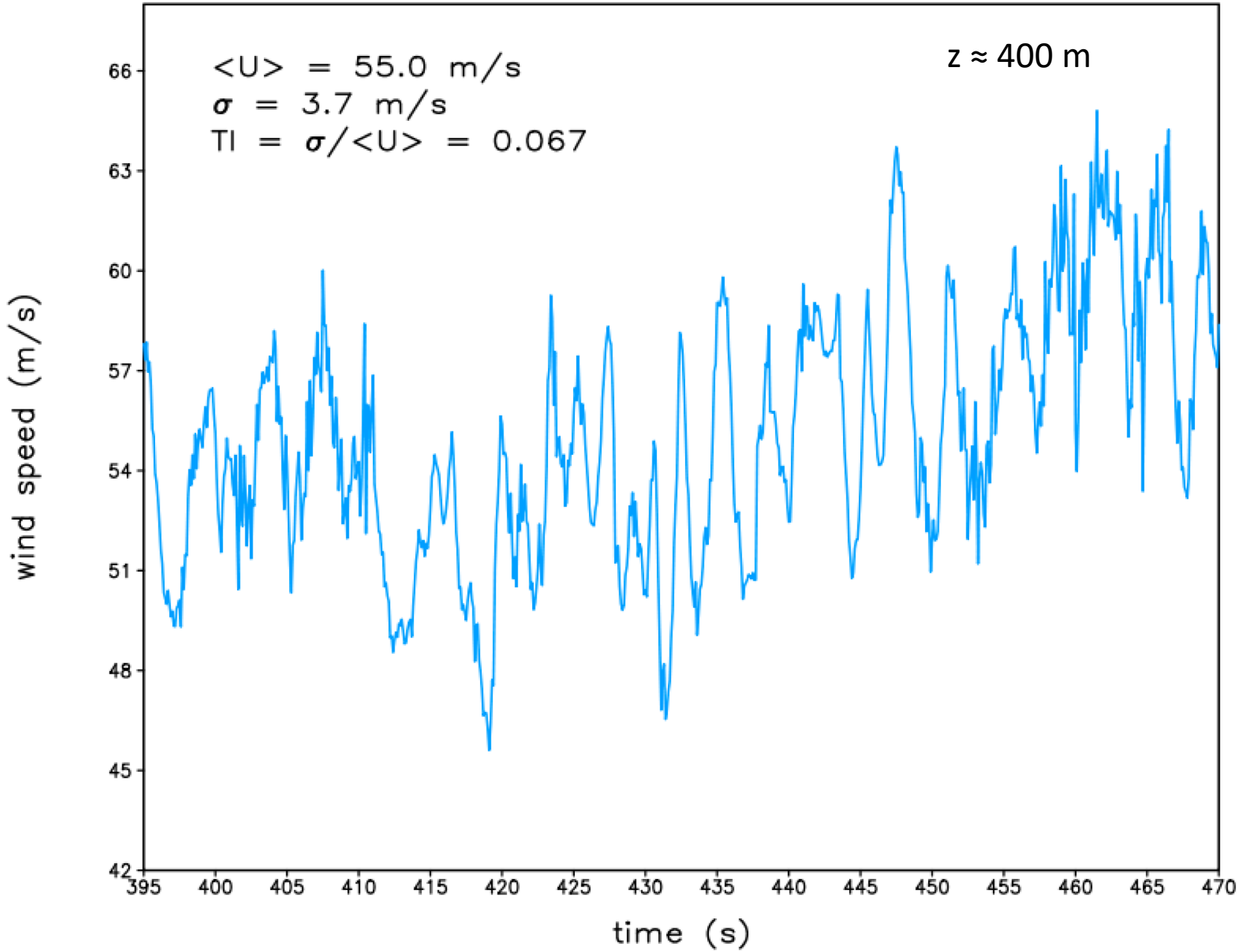
1. Using Coyote data to evaluate simulations

2. Using simulations to interpret Coyote data

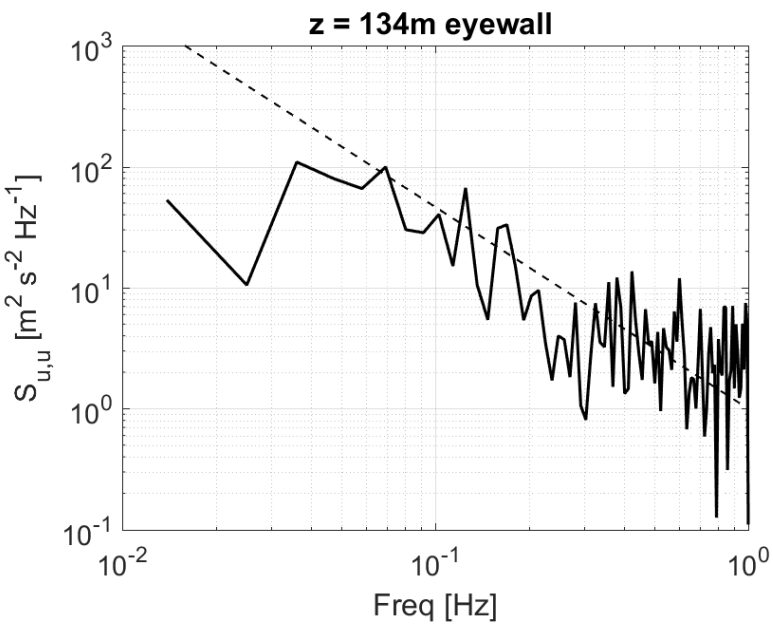
Coyote data: Flight 3 (altitude)

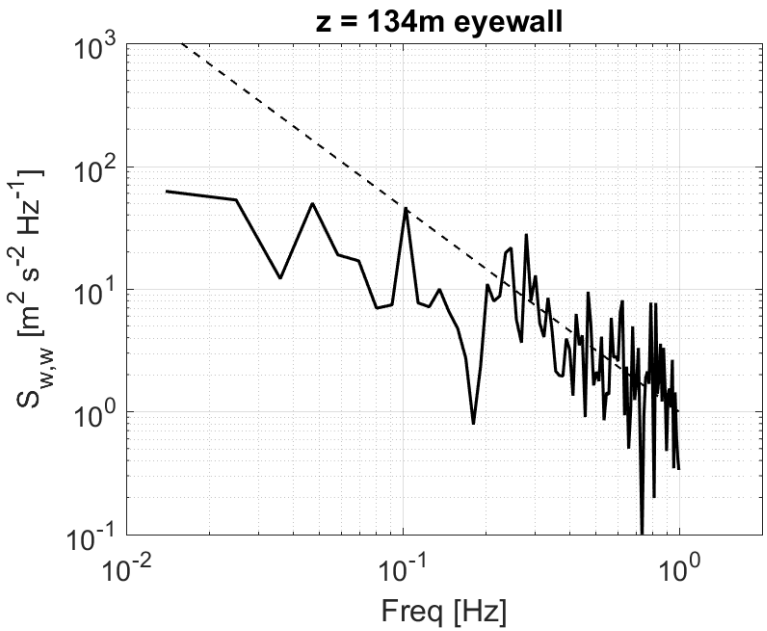


A segment from Coyote 3



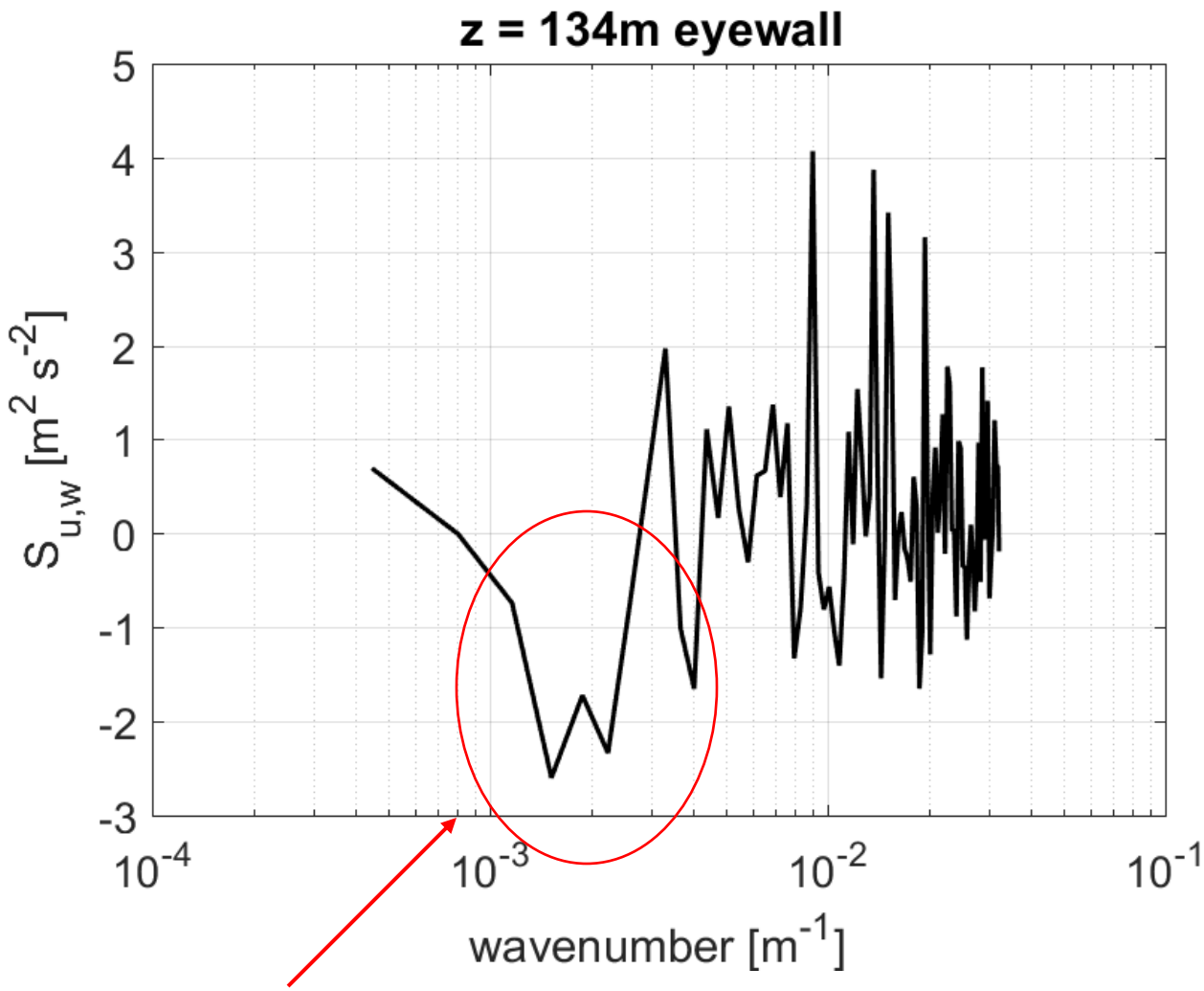
Spectra of along-wind (u) and vertical (w) velocity





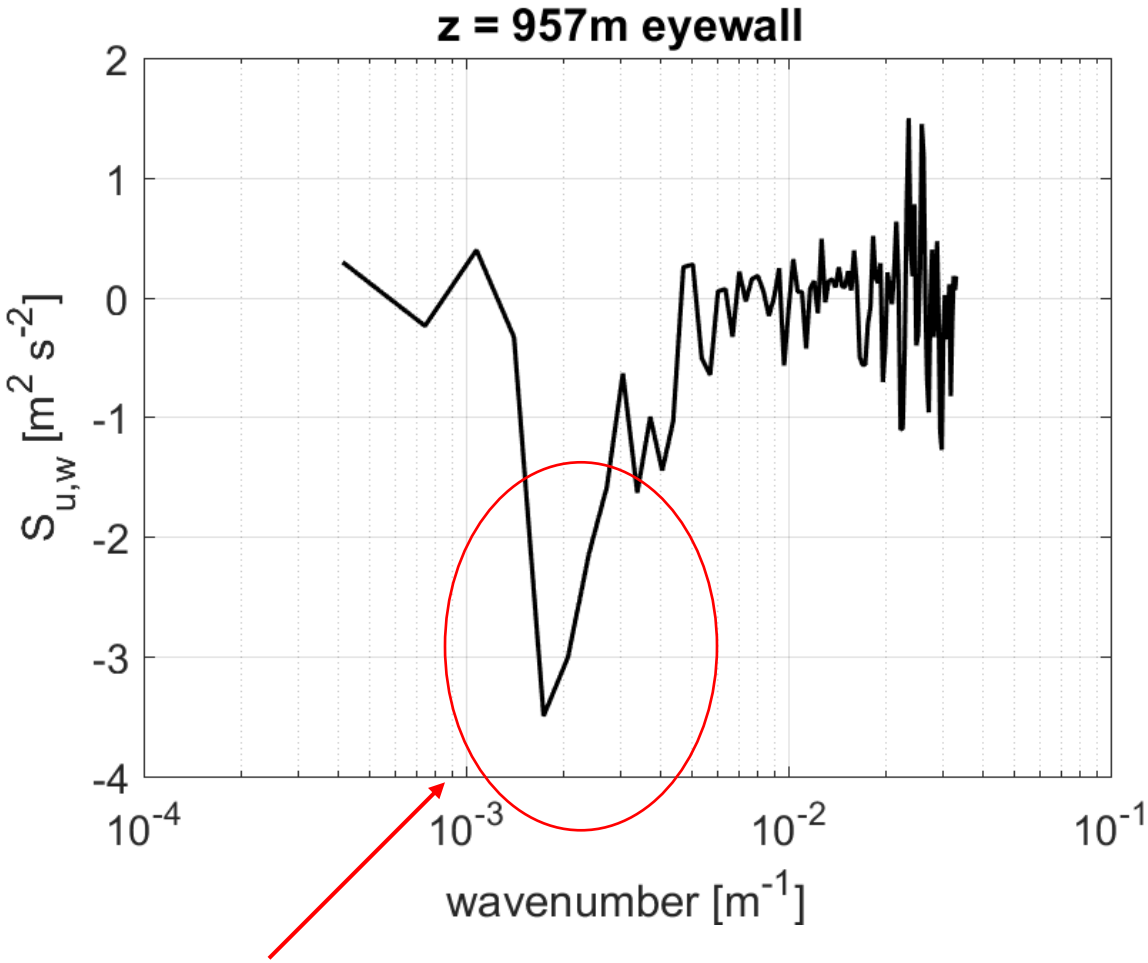
- The spectra of u and w at frequency > 0.5 Hz generally follow the -5/3 slope (black dashed line), indicating the wind retrieval is reasonably good.

Cospectrum of u and w



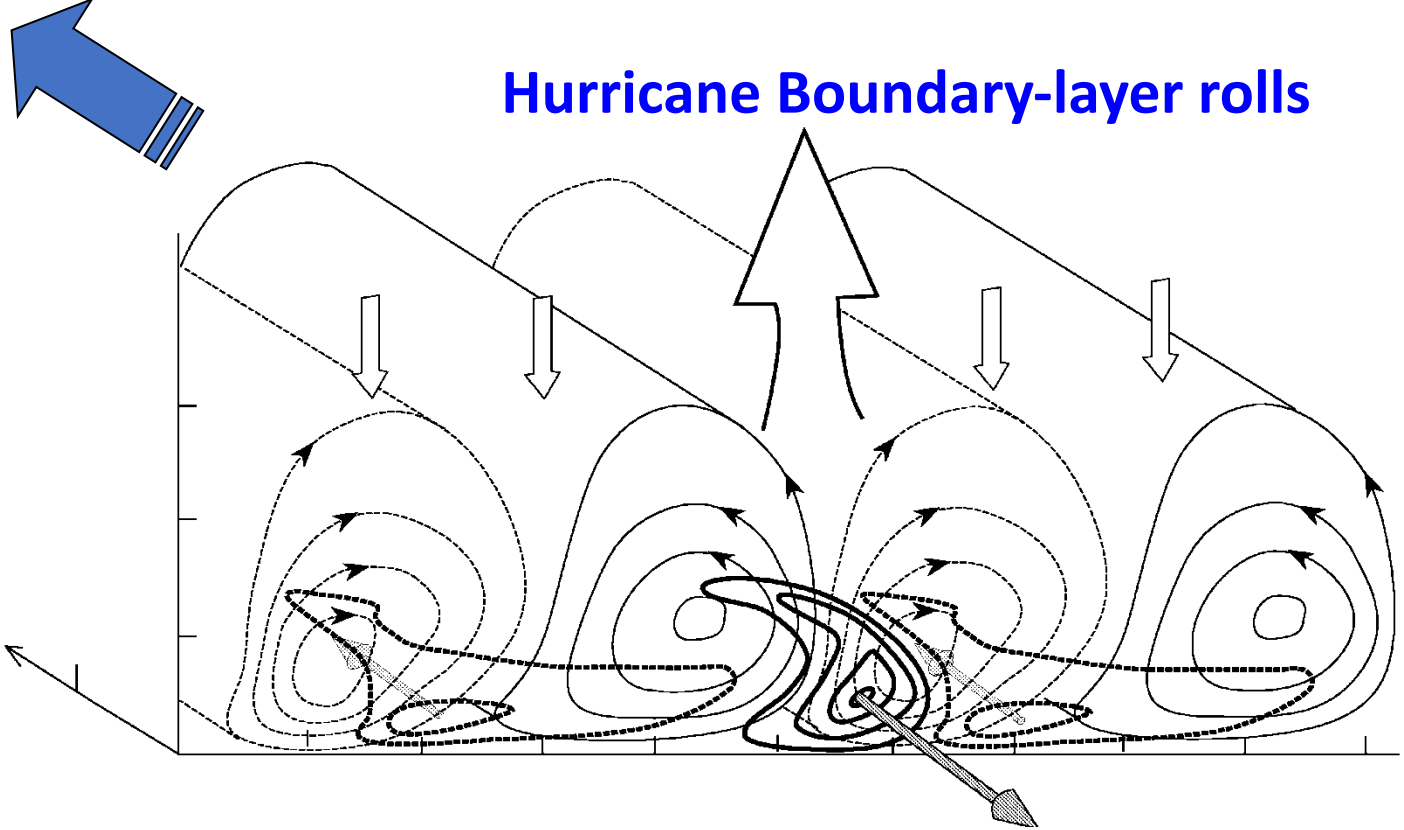
- Strong downward transfer of momentum flux is caused by sub-km scale eddies.

Cospectrum of u and w



- Strong downward transfer of momentum flux caused by sub-km scale eddies is seen near the top of the boundary layer (z=~1km).

Hurricane Boundary-layer rolls

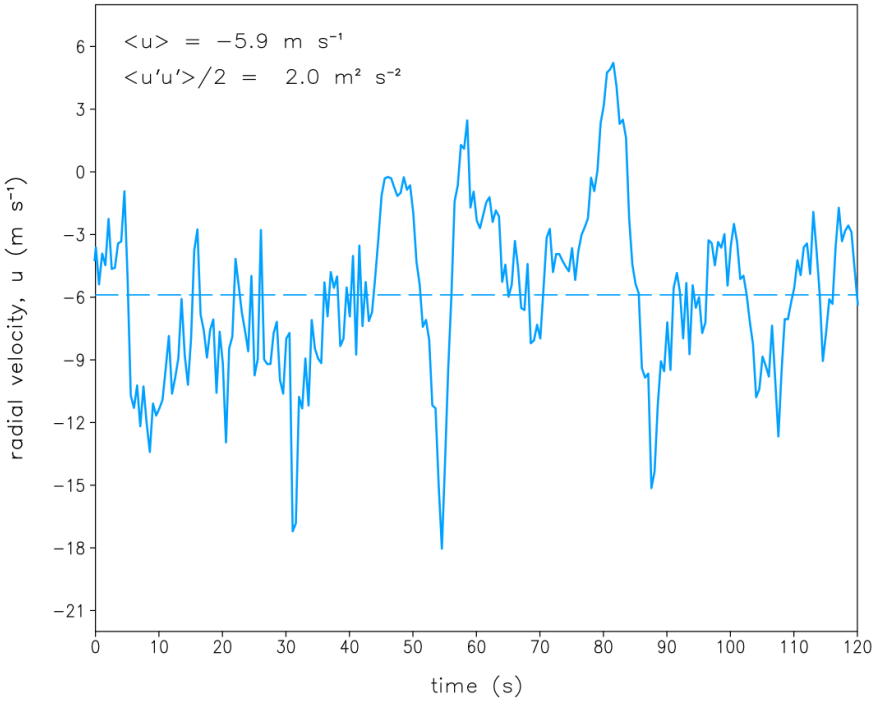


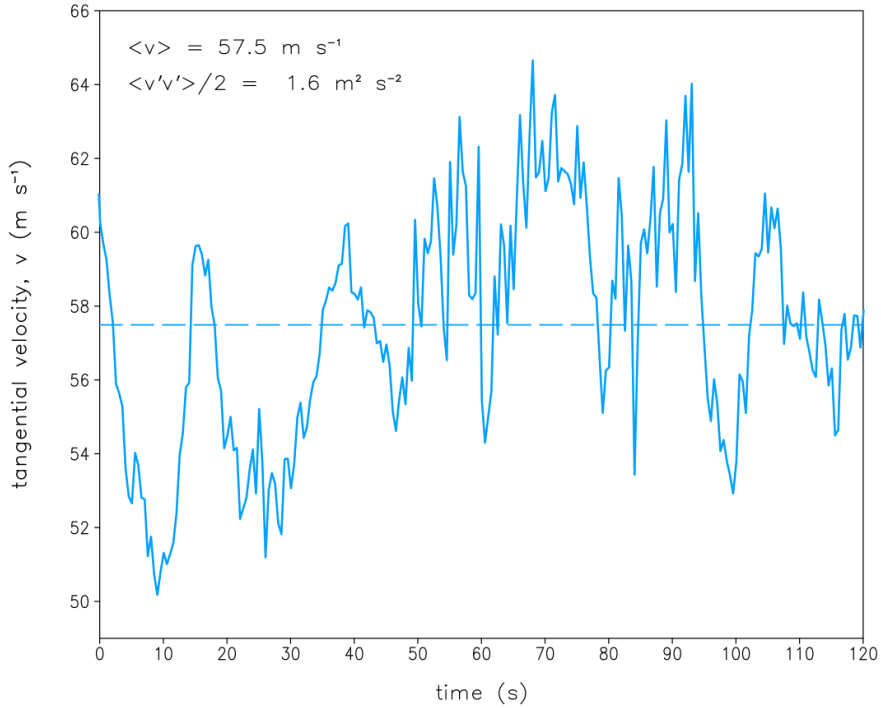
Wavelength: Larger-scale structures ~ 1500 to 2000 m
Smaller-scale structures ~ 300 to 700 m

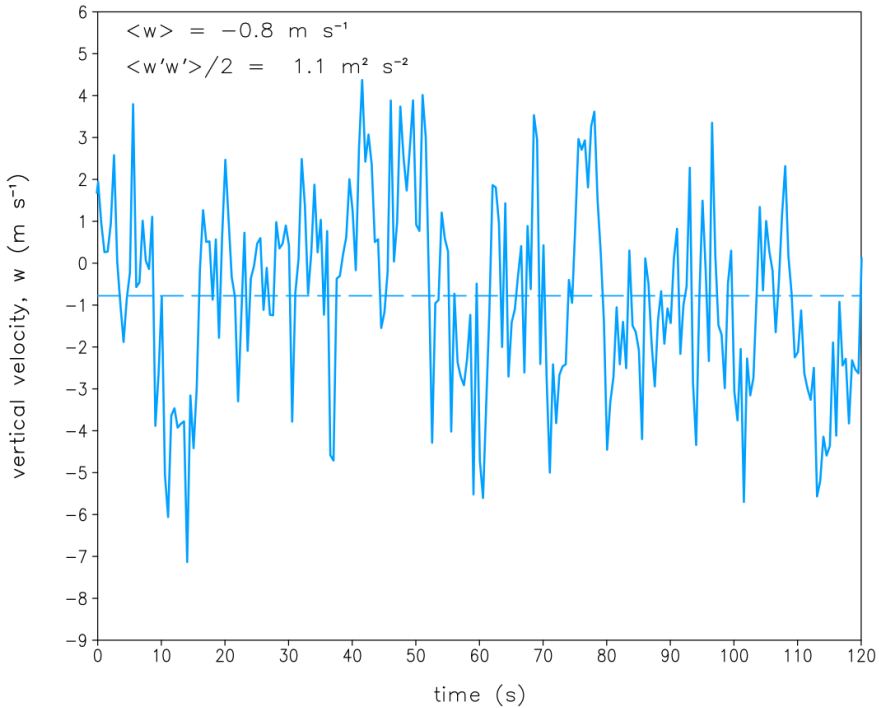
<u>Along-roll</u> velocity Perturbations: +/- 7 m s^{-1} typical
up to +/- " 10s of " m s^{-1} small-scale

Orientation: Typically along-mean wind, ± 30 deg

Prevalence: Roll-scale structures common, (35% to 70%)
Streak-scale structures: ***Most likely usually present***





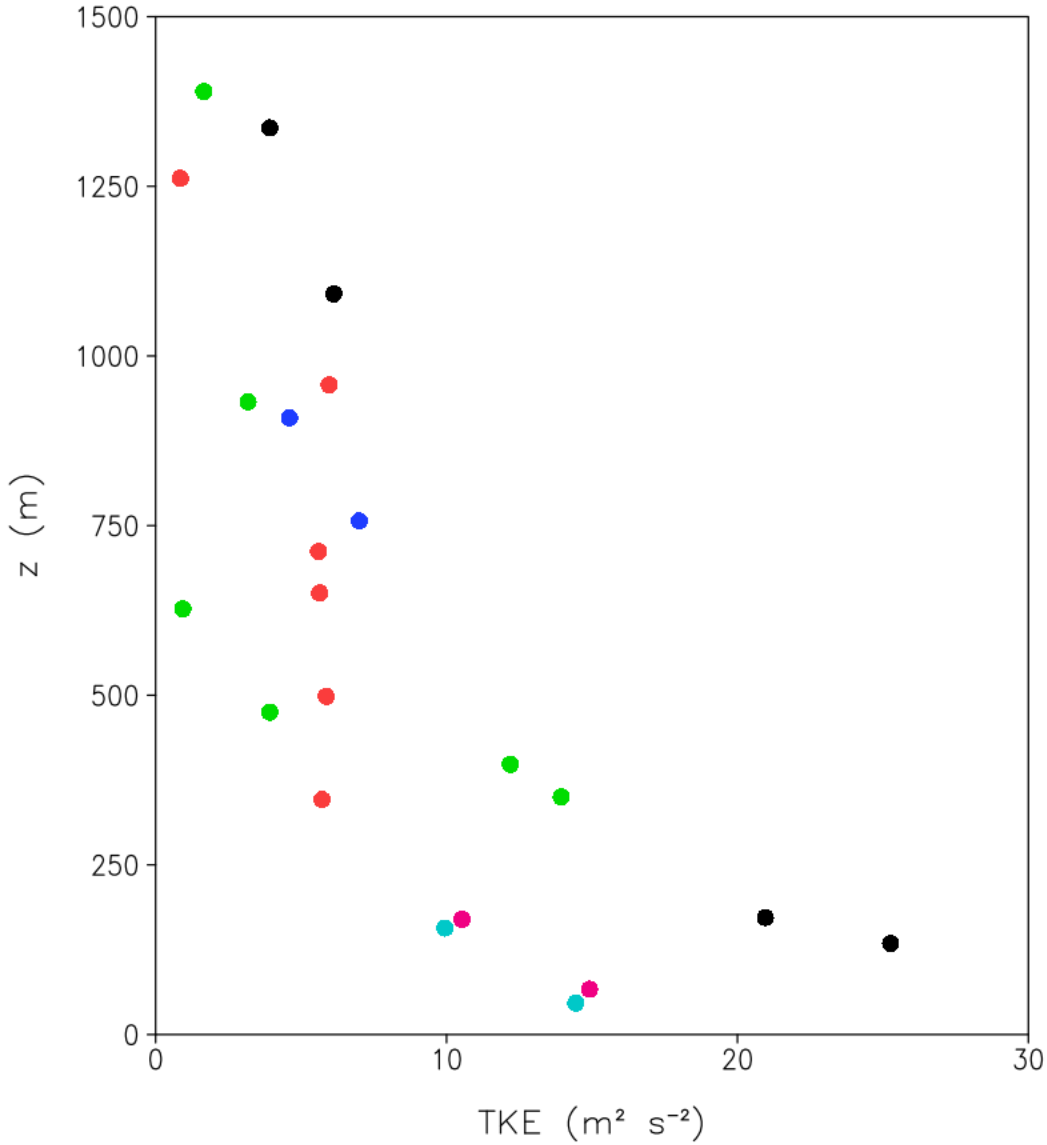


Turbulence kinetic energy:

TKE = (<u'u'> + <v'v'> + <w'w'>) / 2

= 4.7 $m^2\ s^{-2}$

Turbulence Kinetic Energy: TKE = (<u'u'>+<v'v'>=<w'w'>)/2



Colors indicate different Coyote flights

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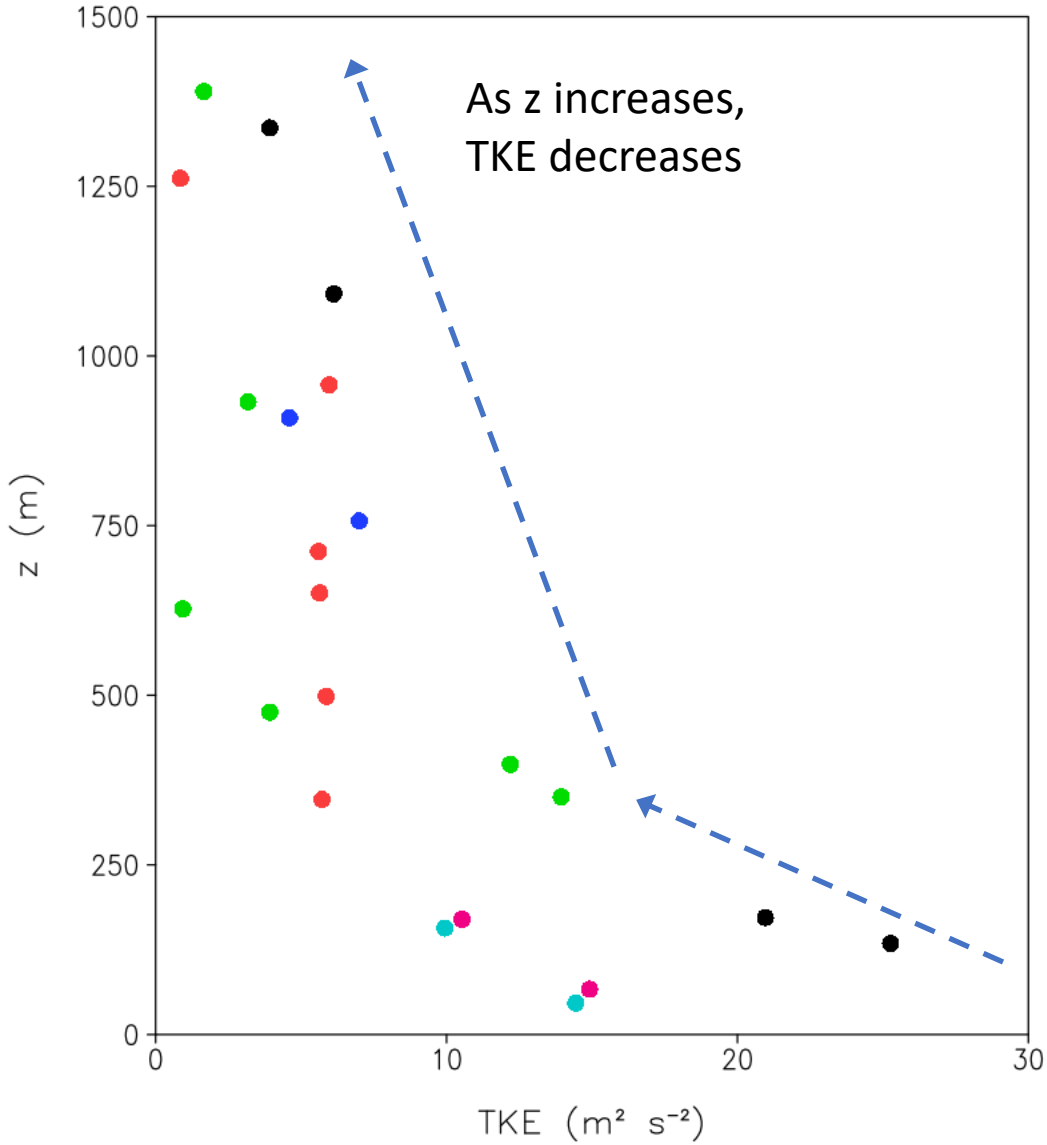
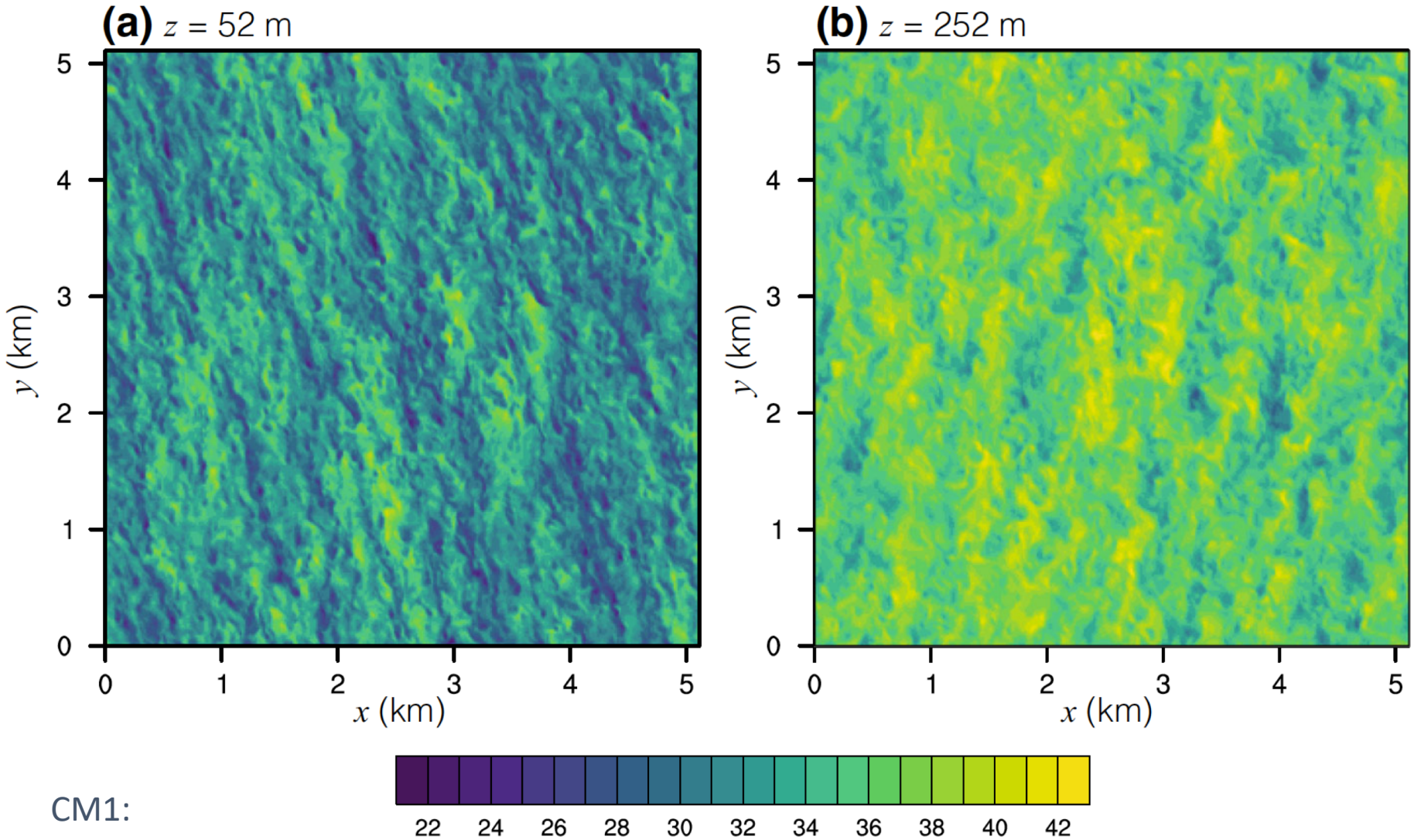


Colors indicate different Coyote flights

Horizontal wind speed (m s^{-1}) from Simple* LES setup

(*small domain, specified wind at top of boundary layer)



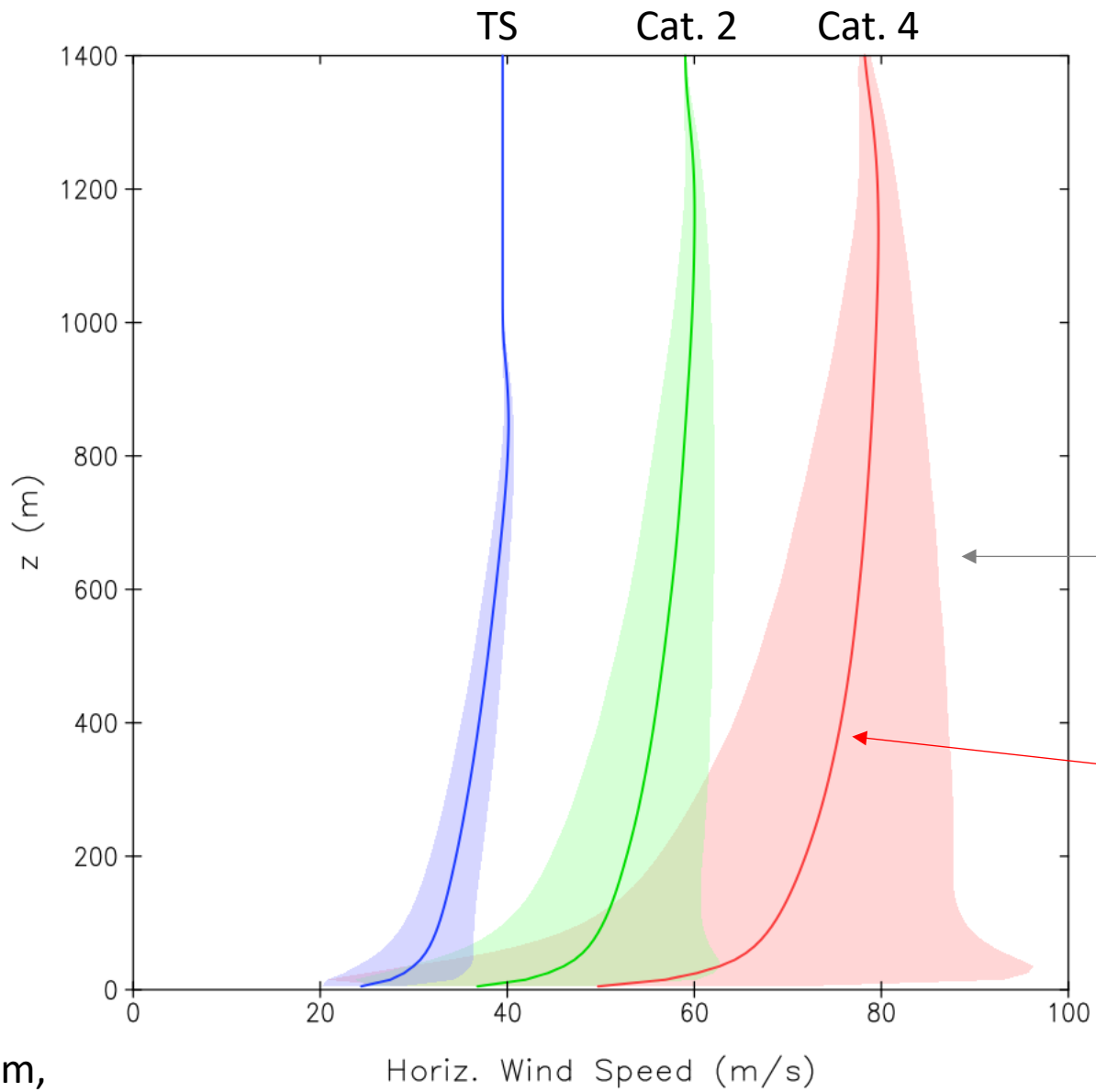
CM1:

$\Delta x = \Delta y = 10$ m,

$\Delta z = 5$ m

Bryan et al. (2017, BLM)

Horizontal wind speed (m s^{-1}) from three simulations



Shading: ±1 standard deviation

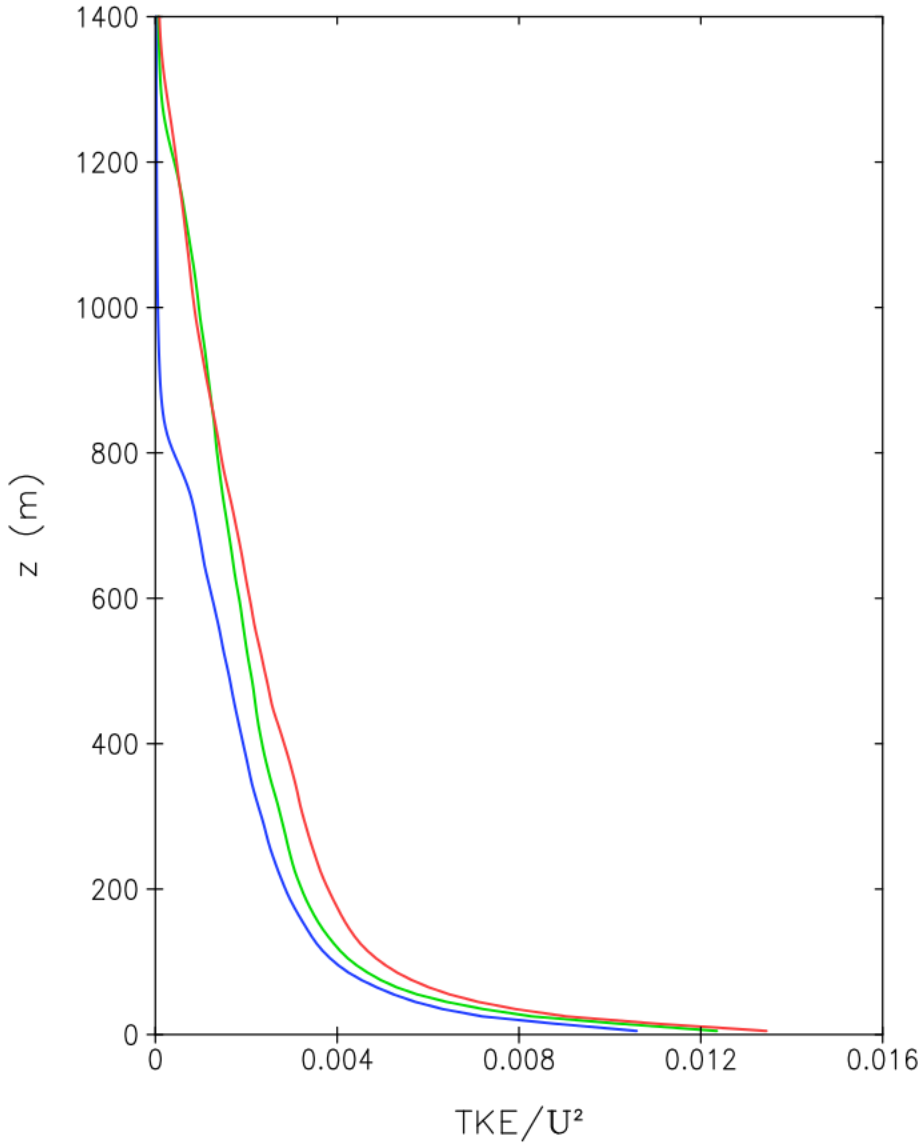
Line: Average wind speed

CM1:

$\Delta x = \Delta y = 20$ m,

$\Delta z = 10$ m

Normalized Turbulence Kinetic Energy: TKE/ U^2 = [(<u'u'>+<v'v'>=<w'w'>)/2] / U^2



CM1:

$\Delta x = \Delta y = 20$ m,

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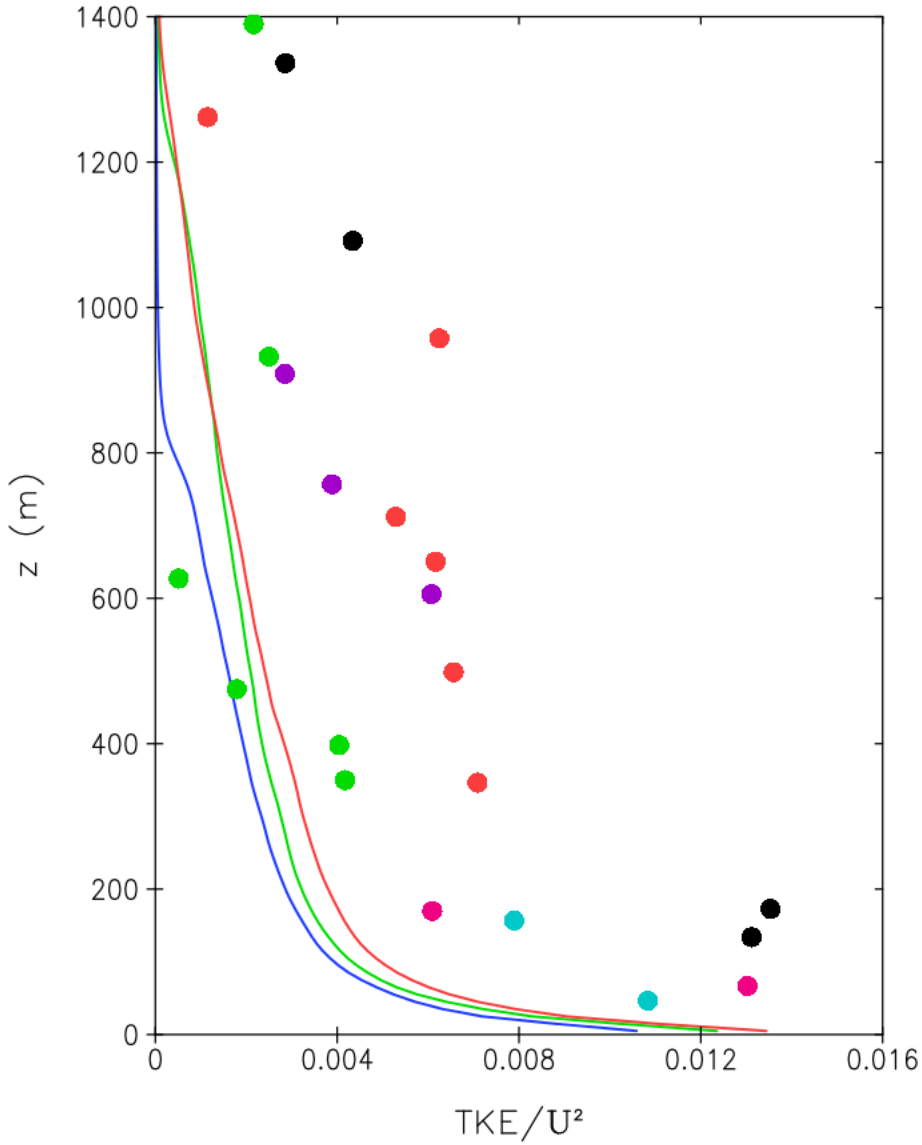
Normalized Turbulence Kinetic Energy: TKE/ U^2 = [(<u'u'>+<v'v'>=<w'w'>)/2] / U^2



Color dots indicate different Coyote flights

CM1:

$\Delta x = \Delta y = 20$ m,

$\Delta z = 10$ m

Using Coyote UAS Observations to Evaluate Large-Eddy Simulations (and Vice Versa)

1. Using Coyote data to evaluate LES
   - Such comparisons are quite rare

2. Using simulations to interpret Coyote data

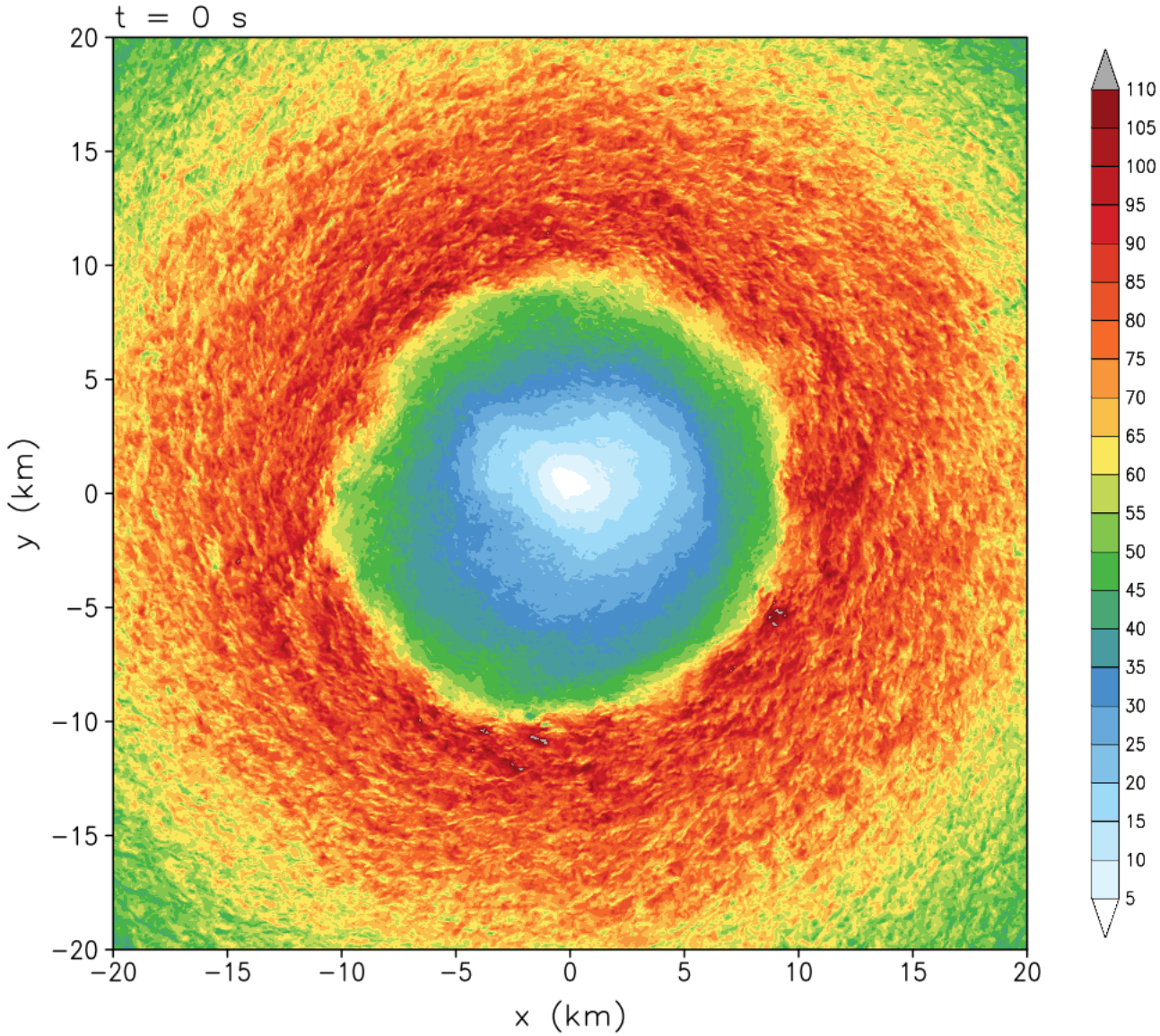
Back to the Complex* Large-Eddy Simulation

(*larger domain, simulate entire hurricane inner core)

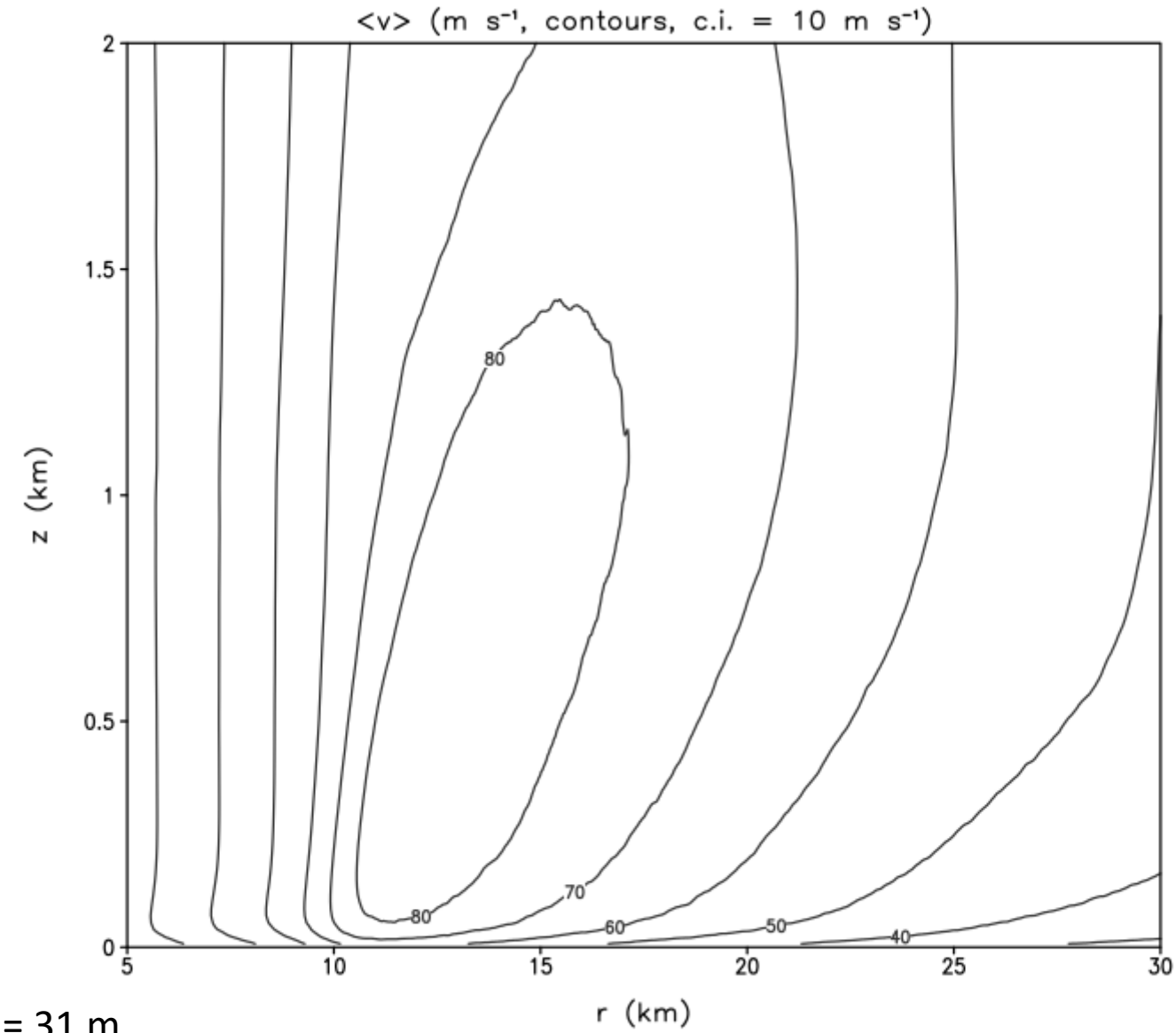
<u>Details</u>:

Wind speed (m s^{-1})
at z = 100m

$\Delta x = \Delta y = 31$ m
$\Delta z = 15.5$ m



Average in time and along azimuths: tangential velocity (v, m s^{-1})

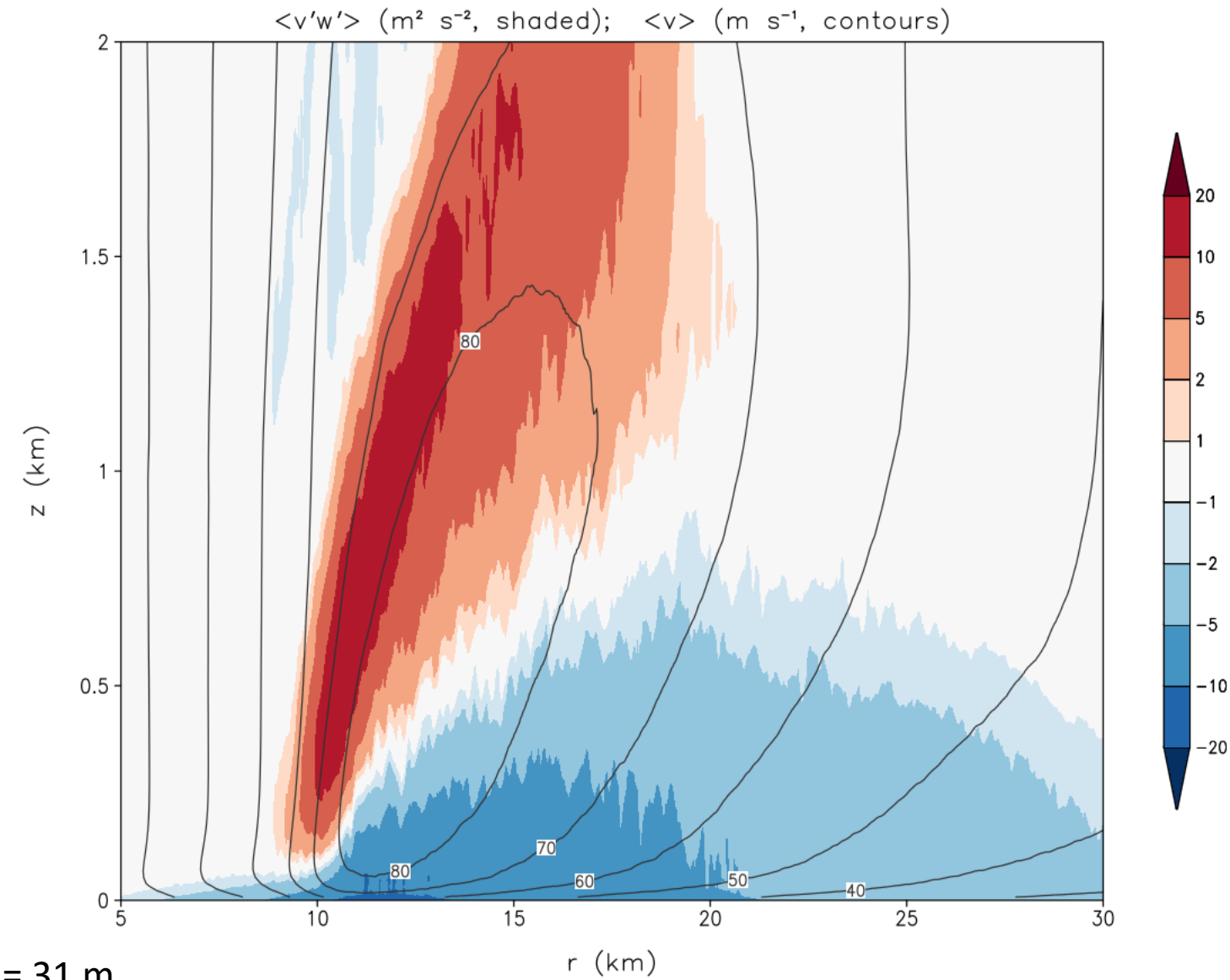


CM1:

$\Delta x = \Delta y = 31$ m,

$\Delta z = 15.5$ m

Average in time and along azimuths: vertical turbulent flux of v ($m^2\ s^{-2}$)

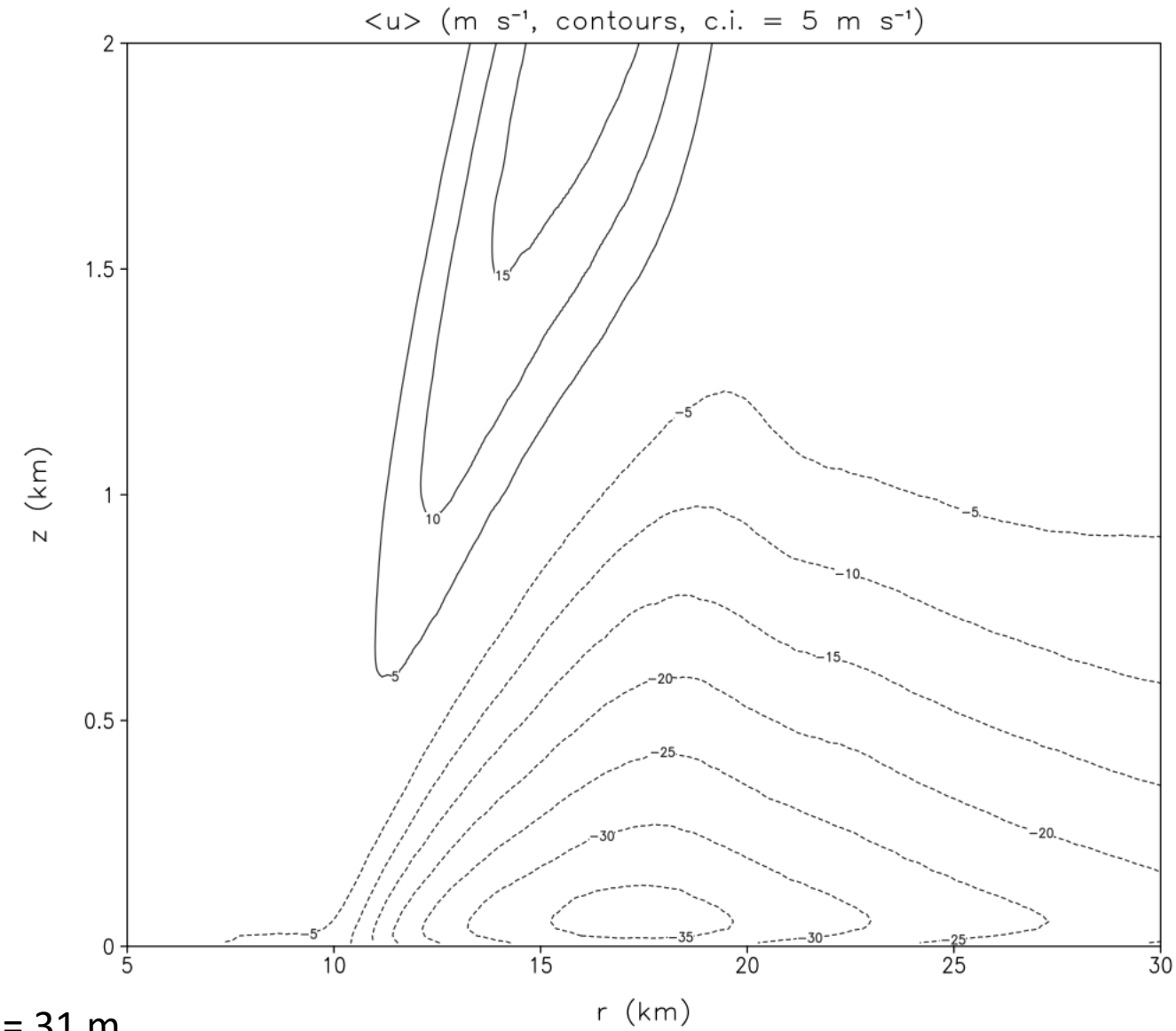


CM1:

$\Delta x = \Delta y = 31$ m,

$\Delta z = 15.5$ m

Average in time and along azimuths: radial velocity (u, m s^{-1})

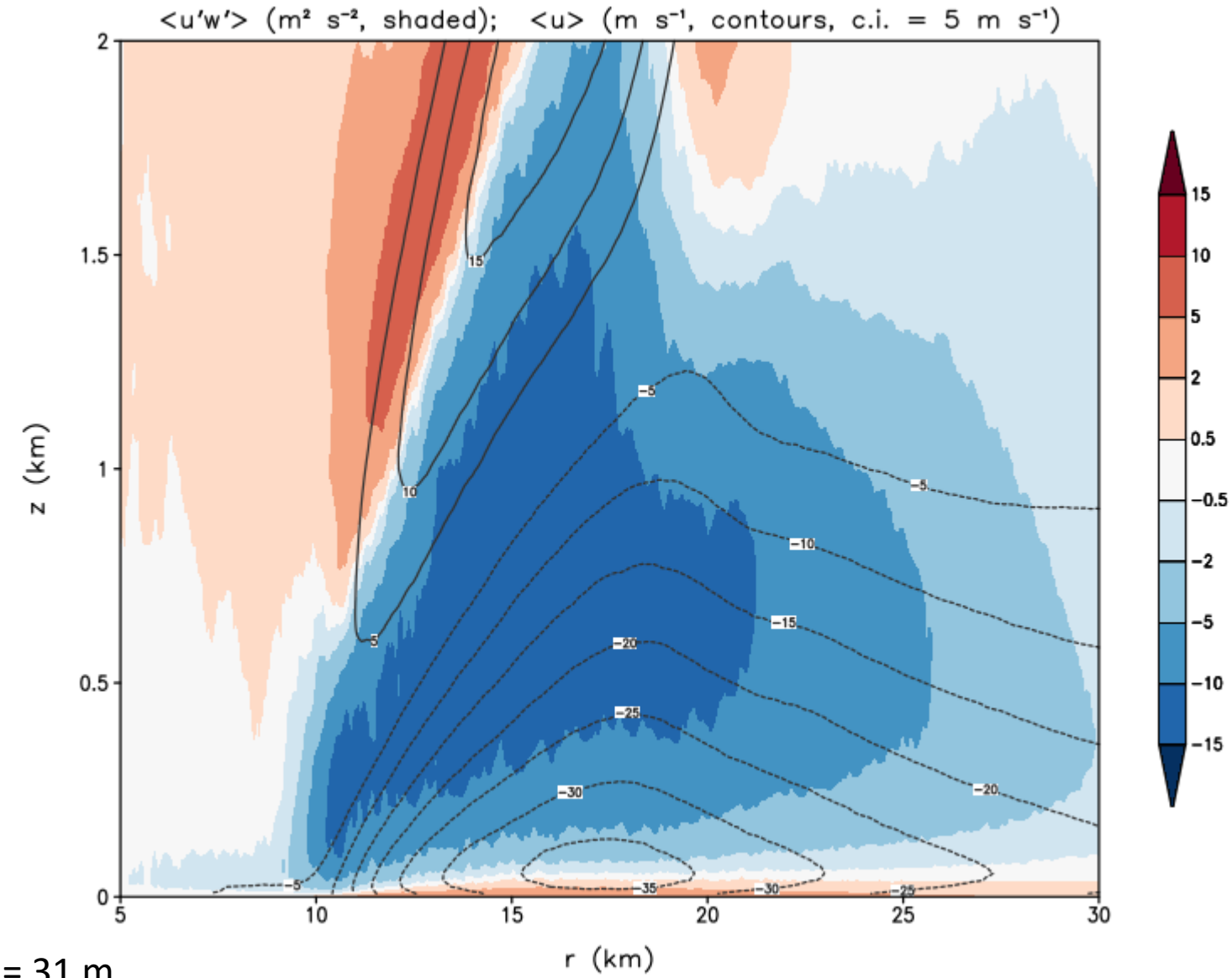


CM1:

$\Delta x = \Delta y = 31$ m,

$\Delta z = 15.5$ m

Average in time and along azimuths: vertical turbulent flux of u ($m^2\ s^{-2}$)



CM1:

$\Delta x = \Delta y = 31$ m,

$\Delta z = 15.5$ m

Summary

- Rare turbulence data in hurricanes
  - (observed and simulated)
- Turbulence metrics from Coyote and LES are comparable
  - Patterns are similar [e.g. TKE (z)]
  - Magnitude [TKE, T.I.] roughly a factor of 2 different
    - (very preliminary)
- Future work:
  - Level Coyote flight legs for $z < 100$ m (for u^*, C_d, C_k measurements)
  - Simulations: calibrate/tune LES based on Coyote data

Acknowledgments: National Science Foundation
NCAR/CISL (computing resources)
NOAA/OAR Office of the Assistant Administrator (Coyote funding)
NOAA Office of Marine and Aviation Operations (Coyote funding & ops)